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SCHENECTADY, NEW YORK

FINAL REPORT

PLASMA ELECTRON BEAM WELDER FOR SPACE VEHICLES

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER

Prepared by

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Research and Development Center
General Electric Company
Schenectady, New York

Contract No. NAS8-11803 Mod. #8
Phase VII

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S-68-1116

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Technical Supervisor
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Marshall Space Flight Center
Huntsville, Alabama

August 1968

FOREWORD

In earlier phases (I through VI) of this contract, a method of welding was developed based upon a new type of electron beam source called "Plasma Electron Beam," abbreviated PEB. A complete PEB welding system was designed, constructed, and successfully demonstrated. This development is described in report number S-68-1026, "Development of a Plasma Electron Beam Welding System," March 1968.

The present report describes related work which was performed as an addition to Contract NAS8-11803 for the purpose of investigating the feasibility of developing a miniaturized, battery powered PEB welding system for use in an earth orbiting vehicle.

SUMMARY

A brief, intensive study has been conducted to evaluate the feasibility of developing a compact light-weight Plasma Electron Beam welding system. Such a system would be battery operated and self contained. It is estimated that it would be 12 inches in diameter and 30 inches long, and would weigh 105 pounds. It would deliver 2 kilowatts of focused beam power to a workpiece for a total welding time of approximately 10 minutes.

Because of its rugged construction and reliable performance, the PEB gun is well suited to this particular application. At the 2 kilowatt beam power level, it has a life of several hundred hours. Welding tests, conducted as part of this study, have demonstrated good quality welds in 6061 and 2219 type aluminum alloys.

Power supply circuitry designs have been analyzed and weights of components have been estimated. The recommended supply uses thyristors (silicon controlled rectifiers) in the inverter circuit which, in conjunction with a transformer and rectifier, convert the 100 volt battery output to 25 kilovolts d-c. This type of circuit is designed to tolerate momentary short circuits, due to gun flash-over, without damage to any of the components.

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I. INTRODUCTION

1.1 Plasma Electron Gun

Previous development programs(1) have demonstrated the welding capabilities of the PEB gun in rough vacuum environments. Since this type of electron gun derives its beam from a low pressure gas discharge, welding is normally done in an inert gas at a pressure of a few microns. Argon or nitrogen is supplied at the correct pressure to maintain a high voltage glow discharge between the hollow cylindrical cathode and the anode cylinder which surrounds it. Positive ion bombardment of the cathode surfaces releases secondary electrons which form a dense plasma inside the cathode cylinder. Electrons are extracted from this plasma, through the circular aperture in the end of the cylinder, by the strong electric field in the cathode dark space. The narrow divergent beam is accelerated to almost full cathode potential in crossing the cathode dark space. When concentrated by an electromagnetic lens or focusing coil, very high energy densities may be obtained for melting or vaporizing any material.

1.2 PEB Welding in Space

To perform welding operations in the high vacuum environment outside the earth's atmosphere, the PEB gun must be enclosed by a cylindrical chamber which contains gas at the correct operating pressure to sustain the beam-forming discharge. For argon, which is normally used, the operating pressure is about 5 microns. A proposed arrangement for automatically maintaining the desired beam intensity and corresponding gas pressure is shown in Fig. 1.1. Supported by an insulating bushing, the PEB cathode extends into the lower chamber into which argon gas flows through an electromagnetically operated needle valve. An increase in gas pressure increases the beam current and draws more current from the high voltage supply causing an increased voltage drop in the resistor. This results in a voltage unbalance at the servo amplifier input which in turn partially closes the needle valve until the beam current returns to its pre-set value. The focusing coil concentrates the beam current at the desired point on the work piece to perform welding or brazing operations.

Experience has shown that the PEB cathode requires a definite minimum spacing from the container walls to promptly initiate and maintain a stable electron beam. This spacing is a function of the gas composition, cathode size and operating voltage. For a 1 1/4-inch-diameter cathode in argon with 25 kilovolts applied, the minimum diameter of the enclosure is about 8 inches and the length is approximately the same. Further reduction of the chamber diameter makes for uncertain starting, current surges, and unstable operation.

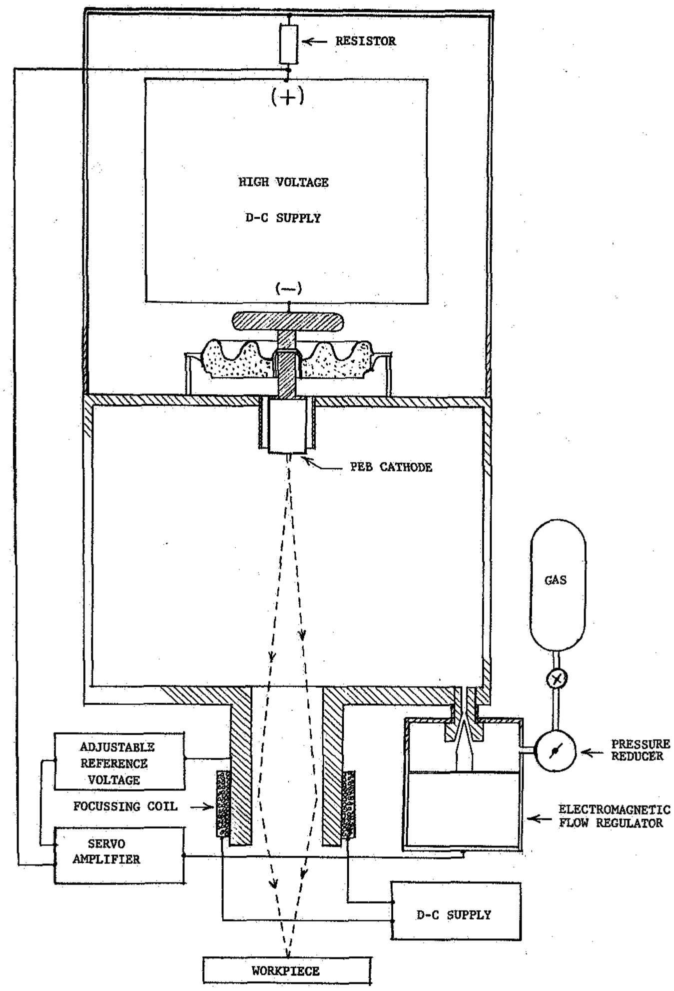

Fig. 1.1 Schematic diagram of a PEB welding system.

If the beam emerges from the cathode chamber into a high vacuum, gas will flow from the chamber at a rate determined by the conductance of the beam tube and by the chamber pressure. To maintain operating pressure in the cathode chamber, gas must be supplied at a rate sufficient to maintain a pressure drop of several microns in the tube. This flow rate is not excessive for a tube 1 to 2 inches in diameter. However, it could be reduced by tapering the beam exit tube and extending it to reduce its conductance.

(1)"Development of a Plasma Electron Beam Welding System," Contract NAS8-11803, Report No. S-68-1026 March 1968.

1.3 Miniaturization of the System

For aerospace applications, the entire system must be as light and compact as possible and must contain its own primary energy source capable of supplying approximately 2 kilowatts of beam power for a total time of 5 to 10 minutes. It must withstand the vibration and stresses associated with launching and must operate reliably after several weeks of inactivity.

Because the PEB gun is simple and rugged and has no hot filament, it appears to be well suited to this application. For the short period of operation required, less than an STP liter of argon is needed. The pressure reducer and flow regulator can, with further development, be made very light and compact.

1.4 Project Definition

The work content of this project, designated as Phase VII, may be stated as follows:

1. Utilizing data generated under this contract, NAS8-11803, determine the feasibility of using a plasma electron beam welding system as the electron beam source for a smaller size welding system.

2. After feasibility has been established, perform a preliminary design and development study for the application of this system as an electron beam source for future Apollo application projects, space stations, and other programs. The proposed plasma electron beam welding system to be considered in this development shall be: (1) miniaturized, battery powered, and self-contained with appropriate controls, (2) less than 105 lbs in weight, and (3) 12 inches in diameter and 30 inches in length.

II. PERFORMANCE DEMONSTRATION OF PEB SYSTEM AT REDUCED VOLTAGE

2.1 New Requirements

Among the requirements imposed by the proposed battery powered system are:

(a) Miniaturization of the PEB cathode chamber.

(b) Operation in the 20 to 25 kilovolt range of cathode potentials.

(c) Delivery of at least 2 kilowatts of focused beam power to the workpiece.

Previous work has been aimed at deep penetration with the fusion zone as narrow as possible. To accomplish this, cathodes were designed to operate at 30 to 50 kilovolts with power inputs as high as 12 kilowatts or more. Since beam penetration improves with increased voltage, little attention had been paid to the development of low voltage PEB welding. Also, no special effort had been made to confine the PEB gun in a small chamber. Therefore, a series of tests was designed to demonstrate the feasibility of operating a PEB system in a confined space and welding at reduced voltages.

2.2 Gun Confinement Tests

Confinement tests were conducted in an 18 inch diameter glass bell jar 30 inches high. It was mounted on a vacuum table and exhausted by a 4 inch booster type diffusion pump backed by a mechanical forepump. The system has a pumping speed of approximately 400 cubic feet per minute at pressures between 1 and 10 microns.

In Fig. 2.1 is shown a photograph of the experimental setup with the glass cylinder removed. The 1 1/4 inch PEB cathode, surrounded by its shield, projects 3 1/2 inches below the top plate on which it is mounted. An electromagnetic focusing lens is supported from the top plate by 3 threaded rods so that its distance from the cathode may be adjusted. On top of the focusing coil is a copper plate with a 2-inch-diameter beam exit aperture. This plate supports a hollow aluminum cylinder which is concentric with the coil. On raising the coil until the top of the aluminum cylinder contacts the top plate, a cathode chamber similar to that shown in Fig. 1.1 is formed.

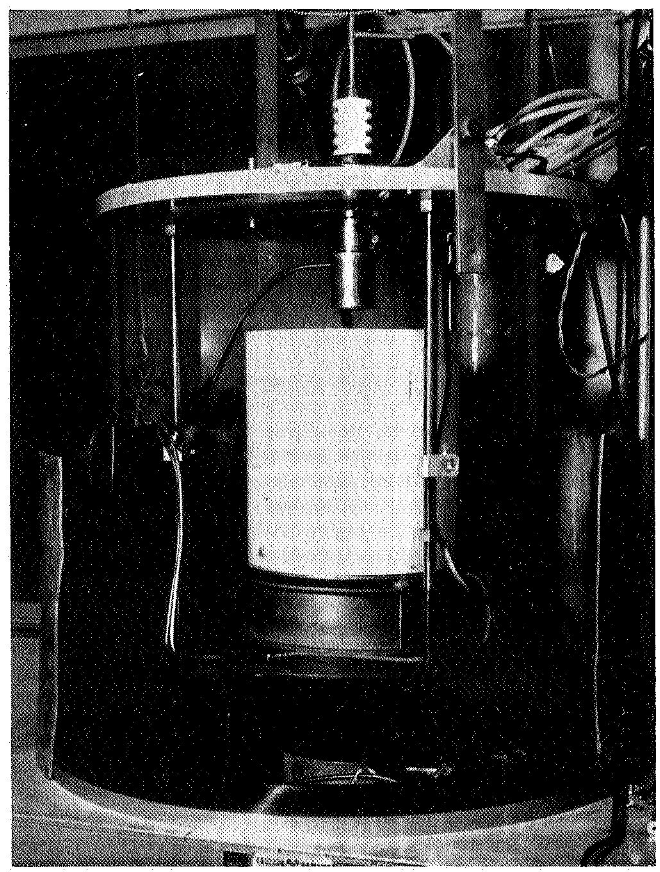

Fig. 2.1 Bell jar system for simulating various size cathode chambers.

By substituting cylinders of various sizes, the effect of varying the dimensions of the cathode chamber may be studied.

When enclosed by a 6-inch-diameter, 5 1/2-inch-high aluminum cylinder, the volume of argon adjacent to the cathode is insufficient to generate enough ions to start the beam-forming discharge. When the gas pressure is increased enough to initiate the discharge, a heavy current surge occurs which trips the circuit breaker. For reliable starting, the electron mean free path for ionization of argon by collision must be of the order of the chamber dimensions. Initiation of the discharge occurs only when the pressure is high enough to fulfill this condition.

After trying a series of confining cylinders of increasing size, successful beam initiation was obtained using a 7 3/4-inch-diameter, 8 1/2-inch-long stainless steel enclosure. However, it was necessary to insert a 5, 000 ohm current limiting resistor in series with the cathode to suppress starting surges. On replacing this cylinder with an 8-inch-diameter, 9 1/4-inch-long aluminum cylinder, satisfactory starting and good beam stability was obtained using the 5, 000 ohm resistor.

Two other cathodes were tested in the 8 x 9 1/2 inch enclosure. Both of these were about the same size as the first one but were of the short stemmed variety, mounted on flat insulators. Because of their short stems and method of mounting, the beam exit apertures were more than an inch closer to the top plate of the bell jar than was the case for the first cathode. Neither of these cathodes performed well in the confined volume. Starting was difficult and a stable beam could be maintained only at current levels well above 100 milliamperes.

2. 3 Gas Flow Measurements

With the first cathode installed in the 8 x 9 1/2 inch enclosure, the argon flow rate into the cylinder was measured by means of a calibrated gasometer. To maintain a 2 kilowatt beam at 25 kilovolts required a flow rate of 20 STP cubic centimeters per minute. Some throttling of the booster pump was necessary to reduce the flow rate to this value. However, it is estimated that the addition of a beam tube and reduction of the beam exit aperture at the bottom of the cathode chamber would add sufficient impedance to make throttling unnecessary.

2. 4 Welding Tests

Since the bell jar, in which confinement tests were made, has no traverse table, welding tests could not be made with that facility. Instead, tests were conducted in the large work chamber used in Phase II of the contract.(1) The 1 1/2-inch-diameter cathode with which this system was equipped was not interchangeable with the 1 1/4-inch-cathode used in the confinement tests. Therefore, the larger cathode was modified for 20 to 25 kilovolt operation by installing a new face plate with a 0. 406-inch-diameter beam exit aperture in place of the 0. 311-inch one, which was designed for higher voltage.

Using the modified cathode, an improvement in efficiency from the previous 65% to 75% was noted. A reduction in the divergence of the beam was also noted (from approximately 10 degrees to 5 degrees).

Previous welding tests with the unmodified cathode using 2 kilowatts of beam power at 25 kilovolts produced penetration depths of less than 1/8 inch in 2219 aluminum alloy. With the modified cathode, an improvement in penetration depth was noted. Figure 2. 2 shows the penetration depth obtained using a 25 kilovolt, 2 kilowatt beam in 6061 alloy (A), and 2219 alloy (B). Both were made at a traverse speed of 20 inches per minute.

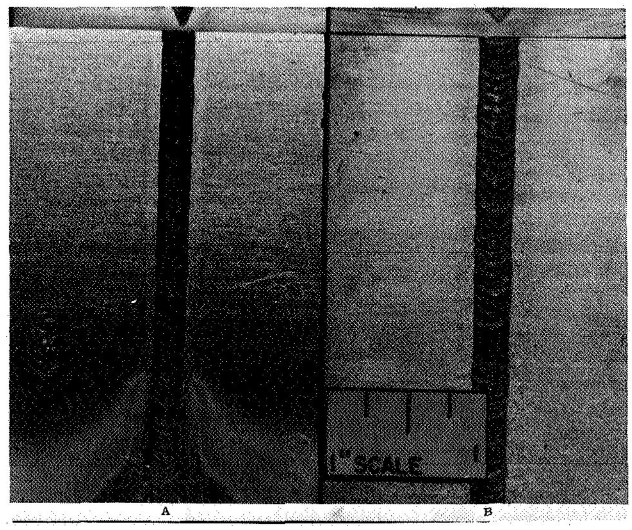

Fig. 2. 2 Penetration tests, (A)-6061 alloy, (B)-2219 alloy speed - 20 inches per minute, cathode kilovolts - 25, cathode current 120 MA, beam current 85 MA.

On reducing the cathode voltage to 20 kilovolts and increasing the beam current from 85 to 100 milliamperes, to maintain the same beam power, the results shown in Fig. 2. 3 were obtained. Figure 2. 3A shows three passes made at 20 inches per minute using focus coil currents of 1. 225, 1. 250, and 1. 200 amperes (from left to right) in an effort to find the best focal point depth for 6061 alloy. Figure 2. 3B shows the corresponding results for 2219 alloy using the same parameters.

These results demonstrate that greater penetration depth can be obtained at the 25 kilovolt level than at 20 kilovolts for the same power expenditure. Previous experience with PEB gun design indicates that smaller sized cathodes can produce smaller focal spots and, therefore, higher power densities at

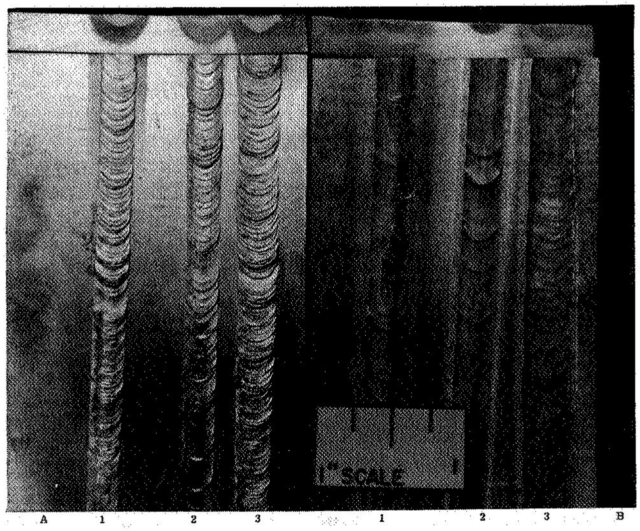

Fig. 2. 3 Penetration tests (A)-6061 alloy, (B)-2219 alloy speed - 20 inches per minute, cathode kilovolts - 20, cathode current 140 MA, beam current 100 MA.

lower voltages. In view of this, the results here reported must be regarded only as preliminary efforts using equipment at hand. A moderate amount of effort applied to the development of smaller low voltage cathodes could produce a considerable improvement in welding characteristics at the 2 kilowatt beam power level.

2. 5 Effect of Cathode Enclosure

While the penetration tests shown in Figs. 2. 2 and 2. 3 were made with no confining enclosure about the cathode, they demonstrate that satisfactory results may be expected using a 2 kilowatt, 25 kilovolt beam from a suitable PEB cathode. Such a beam would be acceptable for the application at hand if it could be obtained from a PEB cathode housed in the available space (8 to 10 inches in diameter and 8 to 9 inches long). The bell jar tests described in subsection 2. 2 have demonstrated that a 2 kilowatt beam can be generated in such an enclosure.

While it was realized that the larger cathode, mounted as it was in the work chamber of the welding system, might not perform well when enclosed, confinement tests were made to try to gain added proof of feasibility. Several unsuccessful attempts were made to initiate the beam with the cathode enclosed by aluminum cylinders from 7 to 9 inches in diameter and 8 inches long, with argon as the operating gas. The higher gas pressures required to initiate ionization in these small enclosures gave rise to excessive surges of cathode current when voltage was applied, causing trip-out of the circuit breaker. However, on substituting nitrogen for argon, the beam could be initiated without tripping the circuit breaker. No welding tests were made with nitrogen because it is considered to be unsuitable for welding some of the metals used in aerospace structures. The difference in behavior in the two gases is believed to be due to differences in their ionization cross sections.

These experiments clearly demonstrate the necessity of using a small cathode extending a few inches into the enclosing chamber (as in the bell jar setup) when space is limited. As previously pointed out, such a setup would require modifications beyond the sculp of the present feasibility study.

2. 6 Conclusions

The preliminary experimental work described has demonstrated that a small PEB gun, suitably mounted, can operate stably at the 20 to 25 kilovolt level in enclosures as small as 8 inches in diameter and 9 1/2-inches-long while delivering a 2 kilowatt focused beam. Argon consumption is not excessive under automatic regulation. Penetration depths in excess of 1/8 inch have been demonstrated in aluminum alloys using a 25 kilovolt, 2 kilowatt beam from a modified 1 1/2-inch-diameter cathode in a large work chamber.

III. POWER SUPPLY

3. 0 High Voltage Power Supply Design

The power supply for the PEB in-orbit welder must operate from a low-voltage battery and provide 25 kV, 120 MA (3 kW) to the load, for a total time of 5 to 10 minutes at maximum current. The weight, including batteries, should not exceed 60 lbs.

Basic Considerations for Minimizing Size

The fundamental method of building such a d-c to d-c converter is to first convert the d-c input to a-c by means of an inverter, then raise the voltage level by means of a transformer, and finally re-convert the a-c to d-c by means of a rectifier. A block diagram of this power system is shown in Fig. 3. 1. The transformer is usually the largest component in this type of converter, and the filter components are also bulky. An output filter is required to smooth the flow of power to the load (less than 2% voltage ripple

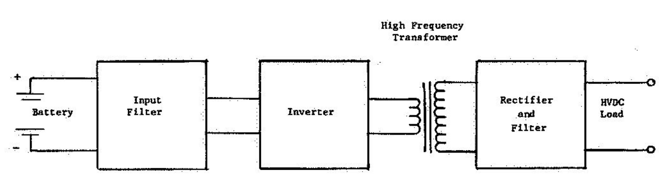

Fig. 3. 1 Light-weight, high-voltage power system.

is desired in the present application), and an input filter is desirable to reduce the pulsation of current drawn from the battery.

If a significant reduction in the size of the power supply is to be achieved, an approach which reduces the size of the transformer and filters is needed. Apart from using the best available materials in the construction of these components, the only parameter which substantially affects their size is the operating frequency of the inverter link. Based on present analysis and experience, a frequency of 10 kHz is obtainable at the 3 kW power level required by the PEB welder and, considering the limitations of presently available components, is close to the optimum frequency for minimizing the size of the converter equipment.

Selection of Inverter Circuit

The inverter, of course, uses solid-state power switches which must operate reliably and efficiently at the high frequency. Either power transistors or thyristors can be considered for this application. The type of switching device selected has a major influence on the optimum battery voltage and the inverter circuit configuration. Thyristors require that the circuit provide some means of forced commutation, which in practice entails the use of a capacitance-inductance ringing arrangement.

However, the suitability of the circuit for operation at high frequency and for supplying a high-voltage d-c output must also be considered. In particular, high voltage systems are subject to arc-overs, which short circuit the power supply output terminals and generate electromagnetic interference which is liable to cause malfunction of the low-level control circuitry. Thus, the power converter must be protected against such faults and limit the current delivered into a short-circuited load, or during the glow-discharge and voltage run-up conditions that prevail when starting the PEB system.

Transistor Inverter

If transistors are selected for the power switches, then the optimum battery voltage is about 28 volts, which is the usual standard for aerospace applications. High performance power transistors have been specifically developed for converters operating at this nominal voltage. In order to achieve the required power level using a transistor inverter, arrays of individual devices in parallel would be necessary. Lossy emitter resistors are required for proper current sharing. For high-frequency operation of high power transistors the switching losses would be quite large, and the base drive power requirements are considerable. Protection of the transistor against faults and overloads would be more difficult than for thyristors when applied in circuits such as those that follow. With transistors, attention must be paid to the avoidance of secondary breakdown, and the manufacturer's specified safe operating area must not be exceeded. Thyristors, on the other hand, are much more rugged in this respect. With the type of thyristor inverter discussed in the balance of this section, the efficiency is higher than would be possible with a transistor inverter of the same size.

Thyristor Inverter

When thyristors are chosen for the inverter switches, a higher battery voltage is desirable. Since at the 3 kW power level, this requires more cells of a smaller current rating connected in series, the battery weight is increased somewhat, since the physical size of the battery cells is not proportionally smaller. A battery voltage of 100 volts is a suitable compromise. This allows a bridge inverter circuit to be used instead of a center-tapped transformer arrangement, so that a series commutating capacitor can be used without an auxiliary coupling transformer. The capacitance required is also reasonable with a 100 volt battery, so that the size of the commutating capacitor can be quite small. Finally, a source voltage of 100 volts is sufficient to ensure reliable firing of the thyristors. If a lower battery voltage had to be used, a serious disadvantage would be imposed on a thyristor inverter. The major advantage of the recommended type of thyristor inverter is its natural suitability for application as the high-frequency link in a high voltage d-c power supply.

A similar type of high-voltage power supply was developed on a program successfully carried out in 1966 in the Electric Power Control Branch of the Electronic Engineering Laboratory of the General Electric Research and Development Center. The objective of this program was to develop a lightweight, compact, power supply to convert three-phase, low-frequency (400 hertz) low-voltage alternating current power to high voltage direct current power. The power supply had an output power of 12.5 kilowatts. The power supply system consisted of:

- A full-wave bridge rectifier to provide a direct current supply of about 270 volts to the inverter.
- An inverter using silicon controlled rectifier clusters and operating at a 10-kilohertz repetition rate to provide voltage step-up.
- A high-voltage, full-wave, single-phase rectifier to rectify the inverter transformer output voltage to direct current.

This program resulted in the building and testing of a breadboard power supply which demonstrated the desired power supply performance as well as its protective features against short circuit and loss of load. Measurements indicated that an overall efficiency of greater than 90% was attained.

Thyristor Converter-Principle of Operation

The method of commutating the thyristors is based upon the series inverter, one version of which is shown in Fig. 3.2. The thyristor pairs P and N are fired alternately and in normal operation the pulses of current through the underdamped R-L-C circuit occupy less than one-half cycle. Thus, each thyristor pair ceases to conduct before the other pair is fired. Two difficulties arise when the load varies over a wide range. First, when R becomes large the current pulses last longer, and if one thyristor pair is still conducting when the other pair is fired, a shoot-through occurs. Second, when R becomes small the oscillations pump the capacitor voltage up to a high value, and the peak voltage rating of the thyristors may be exceeded.

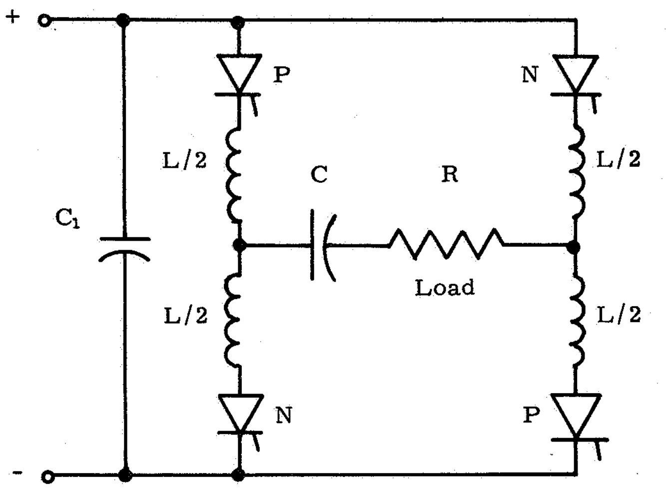

Fig. 3.2 Series inverter.

For a direct-current to direct-current converter application, these problems are solved by the circuit shown in Fig. 3.3 which was developed at the General Electric Research and Development Center. The first problem (with R large) is solved by using a capacitive input filter, C_2, for the load, which maintains a stiff voltage sink. The current pulse duration now remains very close to $\pi\sqrt{LC}$, one-half cycle of the natural period of the series L-C commutating circuit, and is independent of the load resistance. The magnitude of the sinusoidal current pulses and the peak value, E_C, of the capacitor voltage, e_C, are

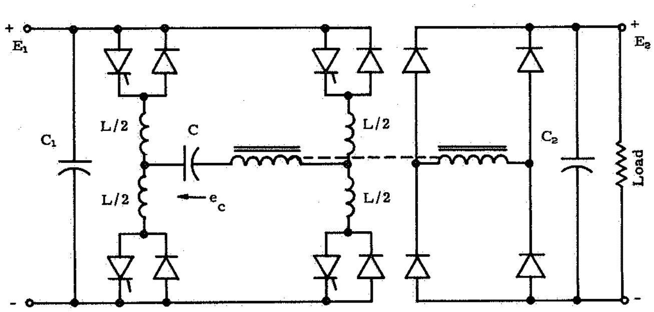

Fig. 3.3 Direct current to direct current converter.

proportional to the direct load current. The difference between the supply voltage, E_1, and the load voltage, E_2, (assuming unity transformer ratio) is quite small and is determined by the losses incurred in maintaining oscillation of the L-C circuit.

The second problem (when R is small) is solved by adding feedback diodes across each thyristor. When the load current increases so that $E_C > E_1 + E_2$, each pulse of current through a thyristor pair is followed immediately by a pulse through the feedback diodes across those thyristors and through the opposite pair of load rectifier diodes. This feeds some of the energy stored in the commutating capacitor back to the direct-current supply and some into the load. The characteristics of the circuit following this change in its mode of operation depend upon any measures taken to change the timing of the firing signals (such as locking-out or delaying the next trigger pulse until the current is zero). The effect is such that, with suitable design, the load may be short-circuited without causing excessive voltage or current stress upon the circuit components. The transition between the normal and the current-limiting modes of operation occurs at a particular point on the output volt-ampere characteristics.

The details of the direct-current to direct-current converter operation described above may be modified somewhat by factors such as transformer magnetizing inductance, winding capacitance, or the addition of auxiliary tuned circuits. Leakage inductance of the transformer is part of the commutating inductance.

Output Voltage Regulation

The load voltage can be regulated by several methods, such as varying the frequency of operation. Regulation by adjusting the frequency of the inverter is relatively inefficient and suitable only if a very small range of control is required. However, this is the case in the present PEB welder application, so that the adjustable-frequency technique should be satisfactory. The inherent battery voltage regulation appears to be quite good, approximately 2% during the intended period of operation, according to the manufacturer's published discharge curves. The amount of converter voltage adjustment that must be provided need only compensate for this droop, plus the inherent droop of the converter output voltage as the load is increased in the normal open-loop mode of operation.

An alternative means of regulating the output voltage would be to interpose a transformerless d-c to d-c chopper regulator between the battery and the inverter. A suitable type of circuit is shown in Fig. 3.4 which will raise the voltage to the inverter by a controllable amount. This arrangement is sometimes called the "flyback" circuit. When thyristor SCR-1 is triggered into conduction, the input filter choke is connected directly across the battery. Thus, the current rises linearly, and the energy stored in

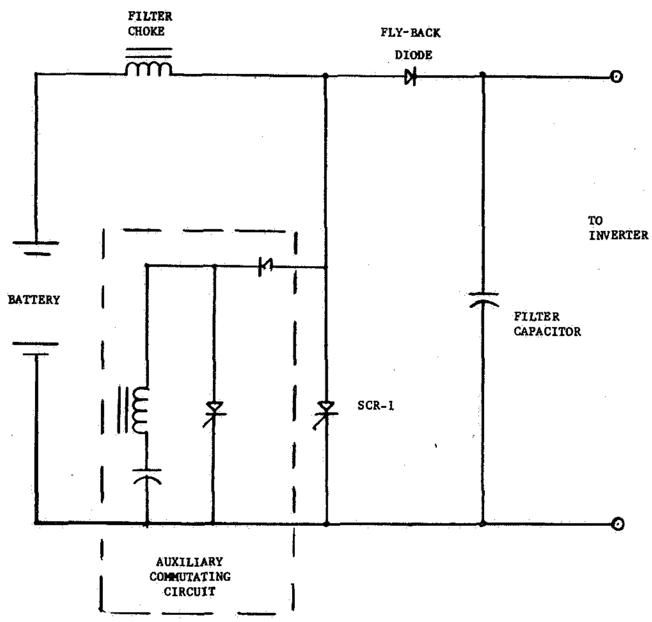

Fig. 3.4 Direct current chopper voltage regulator.

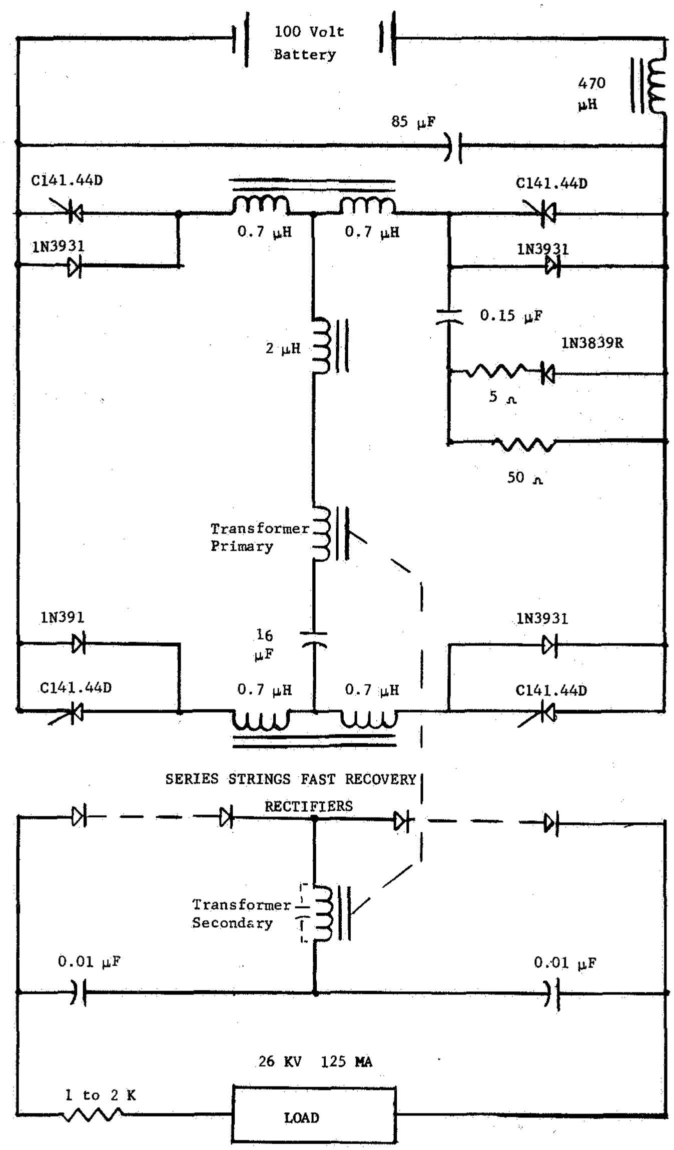

Fig. 3.5 Detailed power supply circuit direct current to direct current 10 kHz inverter.

the choke increases above the average level. After SCR-1 is turned off by the auxiliary commutating circuit, the excess energy in the choke is delivered to the filter capacitor through the flyback diode, raising the voltage on that capacitor. Regulating action would be obtained by adjusting the duty cycle or repetition rate in response to an output voltage error signal.

The chopper converter adds another stage of power conversion, and would be advantageous only if a large voltage variation were required. However, in the event that the recommended technique of inverter frequency adjustment proves to be unsatisfactory, a chopper regulator could be incorporated with very little additional weight. The filter components are already included as part of the input circuit of the inverter. A loss in efficiency of a few percent could be expected, and some additional control circuitry for the chopper would, of course, be necessary.

3.1 Detailed Description of Power Supply

Inverter Elements

A more detailed circuit diagram for the proposed converter circuit adapted to a high-voltage supply is shown in Fig. 3.5. A full-bridge inverter configuration is selected in preference to a half-bridge or center-tap circuit, because it gives better component utilization.

Semiconductors

The four thyristors will each be a cluster of high-speed cells, General Electric Type C14144. The highest voltage grade (400 volts) will permit the inverter to operate from 106 volts direct current, and the circuit can be designed to maintain the working peak voltage well within a safe limit under all conditions. For the packaged equipment, it will be desirable to obtain the matched set of thyristor cells without the standard bulky package, for mounting on a specially designed heat sink. Specifications of the heat sink temperature determines the power capability of the thyristors and, together with the method of cooling, determines the size of the heat sink required.

The feedback rectifier diodes connected in inverse-parallel with each of the thyristors must have a fast recovery characteristic and have the same voltage rating as the thyristors. Their current rating can be relatively low (in the order of 35 amperes) for normal operation and for transient excursions into the current limiting region, such as required during start-up and load flash-over. However, it may be deemed desirable to design the equipment to operate continuously into an overload, in which case the current rating of the feedback rectifiers must be increased to a value comparable with that of the thyristors. The feedback rectifiers are the only components whose size is greatly influenced by operation in the current limit region.

An R-C snubber filter must be connected across each thyristor-diode pair to suppress voltage spikes and limit the dv/dt applied to the thyristors. These snubbers account for an appreciable fraction of the circuit losses. When the thyristors are fired, discharge of the snubber capacitors through the low resistance is blocked by a small auxiliary diode. A larger shunt resistance is provided for this discharge, thereby limiting the thyristor di/dt and switching loss.

Reactive Components

Four commutating inductances are shown in Fig. 3. 5, one in each leg of the bridge. These inductances may or may not be coupled. The amount of coupling has considerable influence on circuit operation in the current-limiting region and is a design parameter for shaping this part of the load volt-ampere characteristic. In construction, litz wire (insulated, transposed strands) and powdered cores are preferred. The leakage inductance of the step-up transformer is an addition to the commutating inductance which cannot be coupled to the others, but this is no problem if the transformer is properly designed. The leakage inductance of a transformer can be calculated with sufficient accuracy to make allowance for it when specifying the inductances.

The series commutating capacitor is designed to ring with the inductances and produce an alternating series of half-sinusoidal current pulses as the thyristors are fired in sequence. The interval between pulses is designed to be sufficient for thyristor turn-off. The magnitude of the current pulses is proportional to the load current, and the L-C components are sized to carry the maximum rated load current before the break-point into the current limit region of operation. A capacitor constructed to have low loss at the high frequency (about 10 kilohertz) is required, such as employing extended foil. Its peak voltage rating is about twice the direct-current source voltage. Metallized polycarbonate capacitors should provide the required performance in a small sized package.

The input filter capacitor should have an order-of-magnitude larger capacitance value than the commutating capacitor. It must carry considerable ripple at twice the inverter operating frequency for single-phase operation. Since a low high-frequency loss is desired, electrolytic capacitors cannot be used. Again, polycarbonate capacitors appear to be most suitable.

Effect of Parasitic Capacitances

The inherent, unavoidable capacitance of the high-voltage winding of the transformer has a significant influence on operation of the circuit. Together with stray capacitance of the high-voltage portion of the equipment, it may be considered as a lumped capacitance (in the order of 100 pico farads or less for the size of equipment under consideration) connected across the secondary winding of the transformer, as indicated by dashed lines in Fig. 3. 5.

When reflected by the square of the turns ratio into the primary side of the transformer, this equivalent capacitance amounts to a relatively small fraction of the series commutating capacitance; but, because of its location in parallel with the transformer, causes a significant shift in the load characteristics. With negligible winding capacitance, no current flows through the feedback rectifiers until a critical, predictable current is reached. At this point, they begin to conduct during the thyristor "off" times and cause the normal, low-regulation region to break sharply into the current limiting region of operation. Behavior of the circuit in both regions is well understood, and a computer program has been developed for calculating the characteristics.

When appreciable winding capacitance is present, the transformer voltage resists the application of a square wave. The energy required to reverse the winding capacitance voltage every half-cycle must pass through the commutating capacitor. The effect is similar to a reduction in the apparent "Q" factor of the ringing circuit in that a considerably larger series capacitance is required; but there is no real loss, since the energy is recovered later. When the thyristors turn off, the winding capacitance starts to discharge through the feedback rectifiers, returning energy to the source. Since the feedback rectifiers now conduct some current during normal operation, the sharp break into the current limit region is blurred and the regulation is somewhat, but not too seriously, poorer, as indicated by the dashed curve in Fig. 3. 6. Conduction of the feedback rectifiers is of some benefit in that a known reverse voltage is applied to the thyristors during their recovery (i. e., the forward drop of the feedback diodes).

Although the capacitance of the commutating capacitor is significantly increased, the series current is very little more. Thus, the capacitor voltage rating is reduced, thereby resulting in about the same KVAR as when the winding capacitance is negligible. To maintain the desired ringing frequency, the commutating inductances must be reduced by the same factor as the increase in capacitance.

The main problem posed by the presence of winding capacitance is to predict the shape of the revised volt-ampere load characteristic and, there-

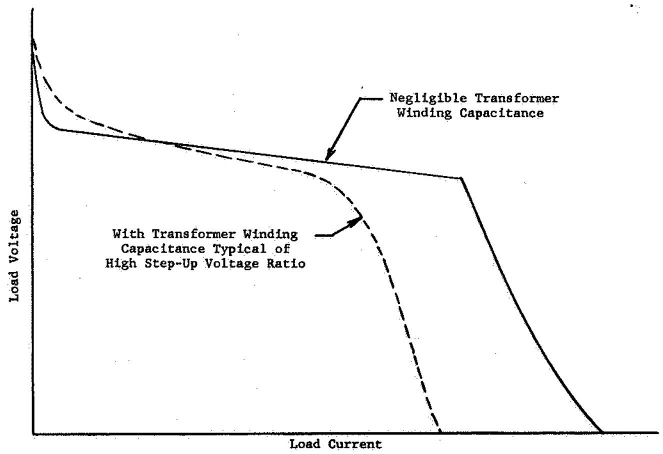

Fig. 3. 6 Typical load voltage - current characteristics, illustrating effect of transformer winding capacitance.

fore, the design of the required L-C commutating circuit. Fortunately, the winding capacitance of a given transformer design can be calculated with reasonable accuracy, and the additional stray capacitance can also be estimated fairly well. When the equivalent capacitance is connected across the transformer of a low-voltage model of the circuit, performance of the model circuit has been found to be in excellent agreement with that of an actual higher power, higher voltage circuit designed on the basis of tests made upon the model.

Another approach is to develop a computer simulation of the circuit, including the lumped equivalent winding capacitance. With an adequate computer simulation, more parameter changes can be readily tried, resulting in a better job of optimizing the circuit. In carrying out this program, it would be proposed to develop such a computer program, conduct an optimization study, and confirm the results by means of breadboard tests as a preliminary step to building the final packaged equipment.

Protective Features

As the no-load condition is approached, both characteristics in Fig. 3. 6 exhibit a considerable rise in voltage which could possibly damage some components. The rise is caused by the tendency of the output filter capacitor to charge up to the peak spike voltage generated within the inverter circuit (stepped up by the transformer). The rise can easily be arrested at a safe voltage level by shutting off the inverter in response to an overvoltage signal. This avoids the need for a bleeder resistor, which involves a loss.

The steady-state current that can be delivered into a faulted load, or in the low voltage, high current region of the PEB characteristic, is limited by the inherent volt-ampere characteristic of the converter circuit. However, the discharge of the output filter capacitors can produce a high initial transient current. A surge limiting resistor is provided to limit the discharge rate, relieving some of the stress on the capacitors. Since the filter capacitors will be much smaller than in conventional supplies, the duty of the surge limiting resistor will be very much reduced.

When a high-voltage arc occurs, it is very difficult to prevent the inverter from "shooting-through"; i. e., both thyristors on one side of a bridge (or all four thyristors) turn on together, thereby applying a short circuit across the input direct-current power source. This malfunction is probably caused by false firing signals produced by improper operation of the inverter control circuit as a result of noise generated by the arc. Even with careful shielding of the low-level control circuits, such faults have been found to occur.

However, a properly designed inverter of the type described will recover from shoot-through faults and resume normal operation after the disturbance. The input filter capacitor will ring with the commutating inductances in series with the misfired thyristors, temporarily reversing the capacitor voltage. The ringback through the feedback rectifiers will turn off both of the thyristors. With a small filter capacitance and the normal commutating inductance, the magnitude of the fault current through the thyristors is well within their repetitive surge rating. The input filter inductance is large enough to limit the rise of the follow-through fault current during the ringing period, such that it is much less than the ringback current and thyristor recovery is assured.

In response to the detection of such disturbances, it may be advisable to block the normal firing signals to the inverter thyristors. This will further ensure recovery of the power supply system. Blocking of the inverter thyristors will cut off current flow into the output filter capacitor within no more than one-half cycle, or about 50 microseconds. This will allow the arc to extinguish. The equipment can be restarted after a suitable delay. It should be possible to resume normal firing of the thyristors, allowing the output to be restored at the approximately constant-current rate determined by the converter characteristics. Alternatively, the manner of starting or restarting can be programmed at some slower rate by suitable control of the inverter frequency.

3. 2 High-voltage Transformer Design

Transformer Magnetic Core Material

The basic criteria which must be considered in choosing the core material are flux density, core power loss, shape, weight, and operating temperature. The high-frequency requirement (in the order of 10 kilohertz) suggests the use of either a ferrite or a very thin steel core material. A secondary consideration may be the desire to minimize magnetostrictive noise generation, since the high frequency sound is objectionable. A suitable ferrite material which has been used previously is MN-60, manufactured by Ceramagnetics, Inc.

Secondary Winding Configuration and Coil Form Material

Proper operation of the high-frequency inverter will require control and minimization of the secondary winding distributed capacity. This probably requires the use of a "pie" or multiple section wound secondary coil. The secondary coil form, required to support and properly place the secondary winding, will play an important role in the specifications of the transformers. The material selected for this purpose must have:

- Low dielectric constant to minimize the secondary distributed capacity.
- Excellent high-voltage insulation to minimize the spacing required and thereby the transformer size.
- Mechanical stability and chemical compatibility with associated materials.

These items must be investigated to assure sufficiently long life under mechanical and thermal stresses and in conjunction with other insulating materials (transformer oil, insulating gas, encapsulation material, etc.).

Primary and Secondary Wire Size and Type

In order to minimize the transformer copper loss, the wire size and type must be carefully chosen. The operating frequency of the transformer will probably require the use of litz wire for the primary winding in order to control the losses.

Transformer Leakage Inductance

This item reflects directly on the operating characteristics of the inverter. Since the transformer connects the inverter "ringing" circuit to the high voltage rectifier circuit, the transformer leakage inductance is effectively placed in series with the inverter "ringing" circuit and therefore must be controlled in order to obtain the desired inverter operating frequency.

3.3 High-voltage Rectifiers

As indicated in Fig. 3.5, a voltage doubler rectifier configuration has been tentatively selected. Compared with a bridge rectifier of the same rating, a voltage doubler rectifier requires only two strings of diodes instead of four, but their current rating is doubled. Two filter capacitors of higher current rating are required. However, the transformer turns ratio is halved, which reduces the winding capacitance reflected into the primary side. This should improve the inherent regulation characteristics of the converter.

The rectifiers must be selected to have certain defined capabilities regarding forward current and inverse voltage standoff. In order to achieve the inverse voltage characteristics required by this power supply, the rectifiers must consist of series assemblies of individual junctions or diodes, each capable of withstanding a fraction of the total inverse voltage (several hundred volts each). Because of high-voltage considerations, heat sinking these diodes is mechanically difficult and space consuming; consequently, the rectifier operating temperature may be high. Thus, diodes should be selected for low forward voltage drop, good heat transfer between the pellet and the case, and low reverse leakage dissipation. Controlled avalanche-type devices with heat-sinking leads are preferred.

A second area that must be investigated is reverse recovery time. Since these diodes are being used to rectify high-frequency alternating current, the diode reverse voltage can be expected to be applied at rates in the order of 1000 volts per microsecond. Thus, fast recovery rectifiers must be selected in order to prevent high losses during the recovery period.

A third important criterion that must be considered in selecting these diodes is their surge current capability. Since occasional arcing of the high-voltage rectifying system to ground can cause high peak diode current, effort should be made to determine the magnitude and the time duration of this current and to select suitable diodes.

3.4 High-voltage Filter Capacitors

Selection of the capacitors will be based on the allowable power supply voltage ripple, the maximum safe capacitor voltage ripple (to control losses and extend life), and the capability of withstanding occasional rapid discharge caused by a high-voltage arc, which may bypass the surge limiting resistor at times. A special package design may be necessary to achieve the minimum weight possible.

3.5 Battery

Electric power to operate the PEB welder will be derived from silver-zinc batteries. This type of battery is capable of delivering large currents for short periods of time, i.e., 10 minutes, and with voltage regulation of the order of 2%. The cycle life of discharge and recharge however is limited to approximately 3 cycles. The variation in voltage discharge characteristics with temperature is small with the best performance being obtained at the higher temperature. For the temperature range of 50° to 90°F, the variation is less than 3%. The energy density is a function of the discharge rate, temperature and size. Densities as high as 49 watt hours per pound can be obtained for this application.

Silver-zinc cells are commercially available that will withstand the pre-launch, launch and post-launch conditions including vibration of 7 g along the major axis and noise levels up to 133 db.

Battery Voltage and Load Current

Batteries made up of silver-zinc cells in series are commercially available, particularly 28 volt units with 20 cells in series. To furnish the 3 kW of power required for the PEB gun from a 28 volt battery would require load currents of the order of 125 amperes and suitable semiconductors for switching the current. In view of this and for the reasons discussed in Section 3 in the paragraphs on "Thyristor Inverter" a battery voltage of approximately 100 volts was selected. The increase in weight and volume of the main battery with the increase in terminal voltage is shown in Table I. The weight of the battery cases was estimated from the weight of a Yardney PM-15 28 volt battery having a 7 pound stainless steel case.

Table I

MAIN BATTERY VOLTAGE VS WEIGHT AND VOLUME

Yardney Cell	No. of Cells	Total Cell Weight (lbs)	Total Volume of Cells (cu. in.)	Case Weight (lbs)	Terminal Voltage	Load in† Amperes
PM-15	20	12.5	183	7.	28	125.
PM-10	36	19.0	296	11.5*	53	66.
PM-5	72	23.0	344	13.*	106	33.
PM-3	144	28.8	460	18.*	212	16.5

*Estimated

†Based on two minute operating intervals with adaquate cooling time between. Total operating time 10 minutes

A series string of 72 cells having a nominal discharge voltage of 1.48 volts would have a terminal voltage under load of 106 volts. The load current would be 33 amperes. This is considered satisfactory for the PEB gun main battery.

Auxiliary Battery

A second 28 volt battery will be used to operate the following:

- Cameras
- Light
- Welding Fixture Motor
- PEB Gun Focusing Coil
- Main Power Relay.

By using this second power source instead of tapping off the main battery for the above devices the power drain on the cells of the main battery will be uniform and the voltage regulation will be improved. Also, the two batteries can be recharged separately.

Silver-zinc cells are available from the Yardney Electric Corporation and the Eagle-Picher Industries, Inc. Both vendors design and manufacture custom batteries and will assume the responsibility for meeting environmental specification. Table II lists the vendor published characteristics of cells that are likely candidates for this application. The Picher cell No. 535 will stand a 1/3 higher current drain for the 10 minutes operating time than the Yardney cell but however is slightly larger and heavier than the Yardney.

The weight of the batteries and enclosing case are as follows:

• Main battery 72 Yardney cells	23 lbs
• Auxiliary Battery 20 Yardney cells	1.4 lbs
• Estimate for enclosing case	13 lbs
TOTAL	37.4 lbs

Table II

CELL CHARACTERISTICS

	Main Battery Yardney PMV-5	Main Battery Picher No. 535	Auxiliary Battery Yardney	Auxiliary Battery Picher No. 485
Cells Only				
Nominal Capacity Amp-Hrs	7.5		1.0	
Nominal Load Volts	1.5	1.5	1.5	1.5
10 Minute Discharge Amps	30.	40.	6.	5.5
Average Volts	1.48	1.45	1.36	1.35
Maximum Weight Filled Oz.	5.1	5.7	1.1	0.9
Overall Volume, cu. in. (incl. terminals)	4.78	5.1	1.18	0.8
Overall Height, in.	2.96	3.3	2.02	1.75
Width, in.	2.08	1.95	1.08	1.06
Depth, in.	0.79	0.79	0.54	0.43
Batteries				
No. Off Cells	72.	73.	20.	21.
Total Cell Weight, lb	23.	26.	1.4	1.2
Total Cell Volume, cu. in.	344.	372.	23.6	17.

IV. CONTROLS

4.1 Gas Pressure

A gas supply and regulating system will be provided to maintain the cathode chamber operating pressure at the proper level and to provide automatic control of cathode current. Argon gas will be stored in a small cylinder at high pressure, and reduced in two stages to the pressure required by the current regulating valve, which is approximately 100 torr. The final regulating valve will be servo controlled by an electronic regulating circuit responsive to power supply current, and will function to hold cathode current at a desired value. The pumping speed of the cathode chamber exhaust line and the range of regulating gas flow will be adjusted to provide proper response time and stable regulation. Gas consumption will be approximately 20 std. cc/min.

4.2 Beam Focusing

The electron beam will be focused on the work piece by means of the focus coil shown in section in Fig. 5.1. The winding is enclosed in a magnetic structure to concentrate the field. To reduce aberration, the inner diameter of the coil is made approximately three times the diameter of the diverging beam as it enters the coil. For the energy and geometry of this system, approximately 1200 ampere-turns are required. Power for this coil will be provided by a separate battery mounted with the main battery, and a series rheostat will be provided for adjusting the current and hence the position of the focal point along the beam axis. By using a separate battery, a change in focus due to droop in the main battery voltage during a welding pass is avoided.

The outer diameter of the coil is determined by weight and power considerations. As the diameter is increased, the weight increases, but the power required and hence supply battery weight decreases. Hence, there is an optimum diameter for minimum total weight of coil and battery. However, with the parameters of this system, the temperature rise in the coil under minimum weight design is excessive; hence, the outer diameter was chosen which yielded an acceptable temperature rise.

4.3 Current and Voltage Control

As described in section 4.1, the gas pressure is automatically adjusted to maintain the current constant at a preset value. A series resistor in the ground return of the power supply supplies a voltage signal which is compared to an adjustable reference voltage. The positive or negative difference voltage is amplified and applied to the windings on the gas flow valve positioner to adjust the current.

The voltage is held constant over the operating range of current by circuitry in the power supply described in Section III. This voltage is factory preset and cannot be changed by the operator. If a spark over in the gun occurs, or the current rises above a predetermined value as a result of excess gas pressure, the voltage falls preventing the current from rising above this value.

4.4 Control Panel

A control panel, mounted on the structure adjacent to the beam exit end, contains the controls and indicating instruments required for operation. These consist of:

(a) Beam Voltage Meter

(b) Beam Current Meter

(c) Beam Current Control Knob

(d) Focus Control Knob

(e) Power Supply ON-OFF Switch

(f) Gas Supply ON-OFF Valve.

4.5 Operating Procedure

Under normal conditions in which the equipment has previously been operated and the beam chamber then has been evacuated and held in this condition, the steps necessary to produce a weld are:

(a) Turn power supply switch on.

(b) Open gas supply valve.

(c) When beam forms, adjust focus control.

(d) Proceed with welding operation.

If the beam chamber has been exposed to atmosphere for a period of time, gas will have been absorbed in the cathode as well as cathode shield and chamber walls. In this case, when the discharge starts, this gas is driven off causing a sudden rise in chamber pressure. This will cause the discharge to go into a glow mode in which no beam is formed and tend to draw excessive current. Because of the current limiting features of the power supply, the voltage will drop to a low value and maintain a low voltage, low power glow discharge in the chamber. This should be allowed to continue for one minute, following which the power supply switch should be turned off. After 30 seconds, the pressure in the chamber will have returned to normal and the steps listed above for normal starting procedure can be followed.

V. PACKAGING AND WEIGHT CONSIDERATIONS

5.1 Objectives

The basic objectives specified in the work statement are that the PEB welder:

(a) Be battery powered and self contained

(b) Weigh less than 105 pounds

(c) Have dimensions not greater than 12 inches in diameter and 30 inches in length.

Additional objectives and specifications furnished orally and in correspondence include:

(d) No vacuum pumps are required since the equipment will be attached to a work chamber furnished by NASA, which is evacuated by a pipe to the outside.

(e) No cooling will be provided by NASA; hence, heat losses must be absorbed in the structure without excessive temperature rise.

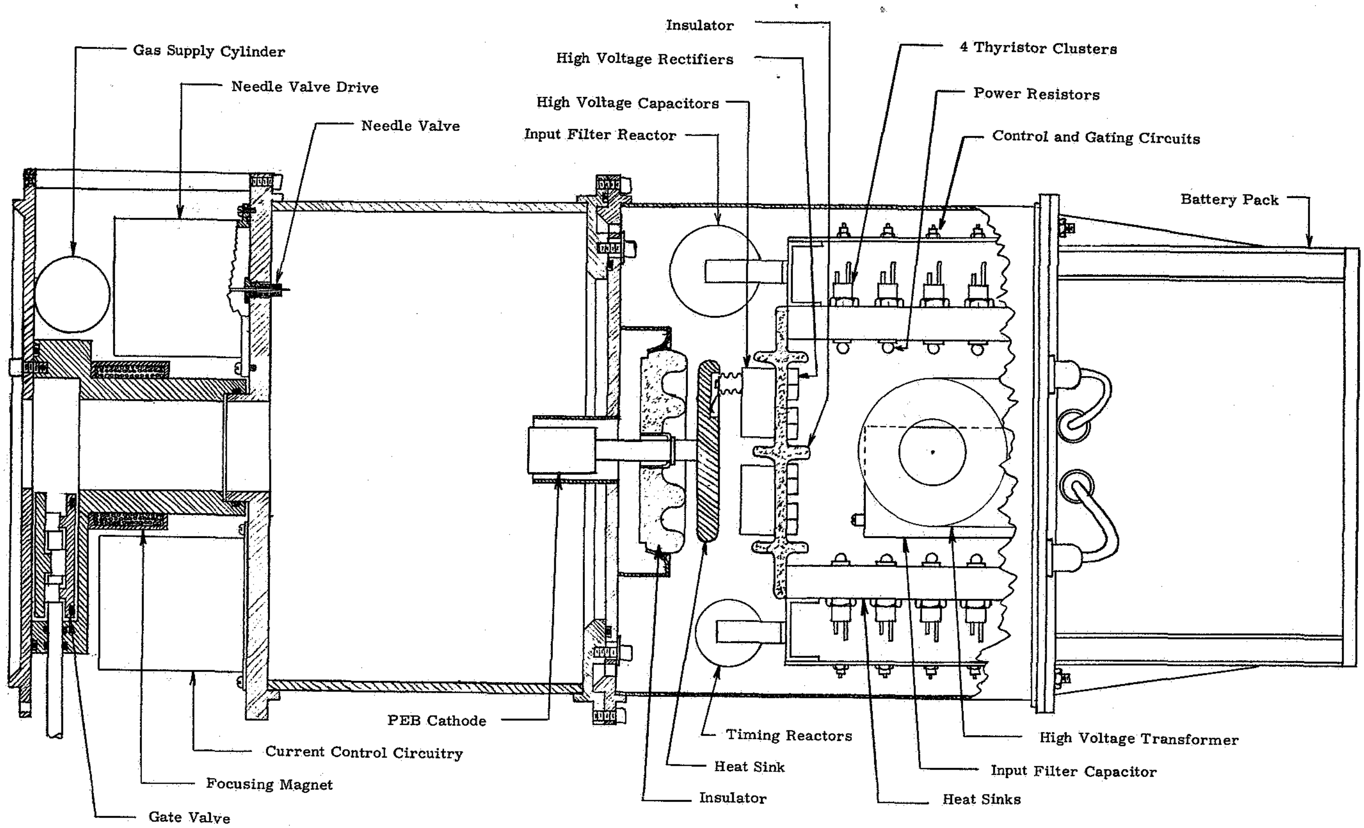

Fig. 5. 1 Arrangement of major components.

(f) Although the required battery life is to be 10 minutes total, it is contemplated that any one period of operation will not exceed 1 or 2 minutes.

(g) The average ambient temperature in the vehicle will be 70°F with a minimum of 50°F and a maximum of 90°F.

(h) The structure and components must be capable of withstanding a steady thrust of 10 g with a superimposed 3 g vibration during launch.

(i) The structure must be designed to mate with mounting brackets and work chamber to be furnished by NASA.

5. 2 Structural Arrangement

For the purposes of this feasibility study a preliminary outline showing the approximate size and arrangement of parts was made, and from this it was concluded that the dimensional and weight requirements could be met. This preliminary outline showing the arrangement of the major components is shown in Fig. 5. 1. In this preliminary design, all of the major structural components are made of aluminum alloy. Beryllium was considered, but because of the extreme precautions required in its machining and use, it was decided to avoid its use provided the weight requirements could be met using other materials.

In the PEB chamber, the flanges and side walls are made heavier than required for structural strength in order to provide sufficient heat storage to prevent excessive temperature rise as discussed in Section 5. 3. On the end of the cathode stem is mounted a block of aluminum to prevent excessive temperature rise in the seal and insulator. The PEB chamber is connected to the evacuated work chamber through a 2-inch-diameter by a 6-inch-long tube through which the electron beam passes, and which provides the required impedance to gas flow for stable operation of the gas pressure regulator.

On the outside of the beam tube is mounted the focusing magnet. In the 5-inch-long space outside the beam tube and focusing magnet are mounted all of the components of the gas pressure regulator including the electronic components of the regulating system as well as the high pressure gas supply cylinder. Also mounted in this space will be the control panel containing the indicating instruments and controls, which are listed in Section 4. 4.

At the end of the beam tube is mounted a gate valve to allow sealing off the beam forming chamber during storage after preflight testing. The end flange is designed to mate with the work chamber furnished by NASA.

The high voltage power supply is mounted in a chamber pressurized with SF_6 gas for high voltage insulation. Since under zero-g conditions gas convection currents will not arise, the gas will serve also as a heat insulator and all heat dissipation of the components must be absorbed by conduction within the internal structure. The battery compartment is separately sealed and is filled with nitrogen gas to eliminate low pressure glow discharge across the

100 volt terminals. Power from the battery is fed to the power supply through external plug in cables. This arrangement allows substitution of a new battery if more than 10 minutes of operation is required.

5.3 Heat Absorption

Since no external heat sinks are provided, sufficient mass of material, appropriately distributed, is provided to absorb the unused energy. Using an efficiency of 67%, for a 2 kW output beam, 1 kW of heat must be absorbed in the PEB chamber. By allowing 10 pounds of aluminum for the chamber, with aluminum having a specific heat of approximately 420 joules/pound/^{o}C, the temperature rise in the chamber for the 1 kW of power will be approximately 15^{o}C per minute. Thus, for 2 minutes of operation the temperature rise will be 30^{o}C.

The focus coil design adapted consumes approximately 40 watts of power and contains 1.25 pounds of copper. The temperature rise in the windings then is approximately 10^{o}C per minute and therefore the temperature rise for two minutes operation will be 20^{o}C.

The heat dissipation in the power supply is 350 watts. By providing 3.5 pounds of aluminum in the heat sinks, their temperature rise will be 15^{o}C per minute or 30^{o}C for 2 minutes of operation. If the heat sinks are initially at the maximum ambient temperature of 32^{o}C (90^{o}F) they will rise to 62^{o}C at the end of 2 minutes. This allows as much as a 38^{o}C temperature difference between the various components and the sink to maintain their temperature below 100^{o}C, which provides an ample factor of safety, particularly since the mass of the components has not been included in this calculation.

5.4 Estimated Weights and Volumes

The outlines of the various components as shown in Fig. 5.1 are based on the preliminary calculations and tests made during this short feasibility study and are subject to modification if a future design contract is undertaken. It does appear that the dimensional and weight requirements can be met. The following is a summary of the estimated weights of the major components:

Beam Section (incl. valve, magnet and gun).	25 lbs
Gas Control Components	15 lbs
Power Supply (incl. case)	25 lbs
Battery Section (incl. case)	37.4 lbs
Control Panel	5
TOTAL	107.4 lbs

VI. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Weld penetration tests made with a PEB gun at the proposed 2 kilowatt beam power level have demonstrated acceptable performance at 25 kilovolts input to the gun. Input power is converted to beam power with an efficiency of approximately 70% by the PEB gun. Other tests showed that the PEB gun can operate stably and reliably in a chamber as small as 8 inches in diameter and 8-inches-long while being supplied with 20 standard cubic centimeters of argon per minute.

A ruggedly constructed PEB gun can be designed which will withstand the stresses and vibration levels encountered during launching of the space vehicle in which it is intended to operate. Weight and packaged volume of the proposed gun fall within allowed limits specified for the system.

A power supply, designed to convert d-c from a 100 volt battery to 25 kilovolts d-c, has regulation characteristics well suited to the PEB gun. This type of supply can withstand surges due to arc-over in the gun without damage to any circuit components or to the gun.

Packaged weights and volumes of the power supply components are estimated to be within limits commensurate with those established for the complete system.

As a result of this study, it is concluded that a reliable miniaturized PEB system, complete with power supply, could be developed which would be 30 inches long and 12 inches in diameter and would weigh not more than 105 pounds. It would be capable of delivering a 25 kilovolt, 2 kilowatt beam which could penetrate approximately 1/4 inch of 6061 aluminum alloy at welding speeds up to 20 inches per minute.

6.2 Recommendations

The following program of work is recommended:

1. Testing of a Partially Miniaturized System -

(a) Design and construct a miniaturized high voltage transformer and test it in the proposed power supply circuit, using components which can be readily procured but not all of which need be miniaturized.

(b) Design and construct a PEB gun suitable for 20 to 25 kilovolt operation, which has higher beam power concentration and higher power conversion efficiency than those presently available.

(c) Make welding tests using the power supply and gun developed in (a) and (b). Instead of a battery, the system would be powered by a low voltage, high current d-c supply.

(d) Evaluate the performance of the system and incorporate desirable modifications.

2. Design and Construct a Fully Miniaturized System -

Utilizing the information gained in the previous program, procure or design and fabricate, miniaturized components to fit into the allowed 30 × 12 inch enclosure. Design and construct mountings, compartments and partitions commensurate with the specified container space and weight limits.

Assemble and test the entire system using a vacuum chamber with suitable pumps to simulate the space environment.

LIST OF ILLUSTRATIONS